Forecasting turbulence over the seas

Turbulence, the leading cause of injuries in commercial aviation, is a particular concern for transoceanic flights, in remote areas where the phenomenon is often worst and pilots have little information. NASA and NCAR (National Center for Atmospheric Research) are working to develop a prototype system to enhance the weather information available to pilots flying over these remote ocean regions.

GATDSSA, the Global Atmospheric Turbulence Decision Support System for Aviation, project will use computer weather models, satellite data, and state-of-the-art artificial intelligence techniques to create a picture of developing storms and other potential causes of turbulence.

"One of the goals of providing automated weather information is to make better planning decisions on where to route aircraft in the first place, then give everyone—pilots, air traffic controllers, dispatchers—a common view of weather." – JOHN WILLIAMS

by J.R. Wilson
Contributing writer

Researchers are developing techniques to give pilots earlier warnings of turbulence in remote areas on transoceanic flights. Until now, little information has been available in these regions, and pilots have had to rely on reports from other aircraft or on satellite data. NCAR is combining advanced technologies and computer modeling to develop clearer pictures of developing storms and other hazardous conditions.

"Oceanic weather is hard, because there isn't any weather radar over the ocean; all we have are pilot reports and satellites," notes John Murray, advanced satellite aviation-weather products (ASAP) project manager at NASA's Science Mission Directorate. "In the past five years, we have developed a lot of tools to improve convective weather and turbulence forecasting, primarily over CONUS [continental U.S.]. Now we are trying to integrate these tools to deal with the oceanic turbulence problem.

"We have given NCAR a number of grants in the past five years to develop and prove convective weather and turbulence products using satellite data. Many of those were joint with the University of Wisconsin, the University of Alabama-Huntsville, and MIT's Lincoln Laboratory. For example, the $912,000, three-year grant we issued to NCAR in July to study oceanic convection and turbulence is an effort to bring together all of the tools developed in the previous five years of ASAP studies."

Guidance for better decisions

The GATDSSA study is focused on improving turbulence decision support systems for pilots, using satellite data to address and improve information the U.S. provides to two world area forecast centers, in London and Washington, D.C. Those centers send out significant meteorological reports (SIGMETs) every four hours and significant weather charts every six hours for preflight briefings to pilots on overseas routes. The intent is to provide more rapid updates and enable pilots en route to request SIGMET updates.

"Sometimes we call it global GTG [graphical turbulence guidance], a play on the CONUS GTG," Murray says, referring to information currently derived from ground-based radars and satellites. "We are aligning this with the U.S. NextGen [Next Generation Air Transportation System] effort, part of which is to provide a 4D weather cube—time dimensions with diagnosis and forecast.

"Our forecast will run from 0 to 36 hr, including 0-3-hr 'nowcasts' that include thunderstorm locations and intensities we can use to derive a probability of convectively induced turbulence. That is one of three major sources of upper atmospheric turbulence—the other two being mountain wave turbulence and clear air turbulence, which is associated with jet stream upper level fronts and shears."

GTG is an "expert system" that combines information

Studying developing thunderstorms on land will aid in predictive modeling capabilities. Image courtesy North Dakota State Climate Office.

Overshooting tops can provide strong evidence of turbulence.

environmental and observational features of a thunderstorm and associating that with an aircraft observation of turbulence. Then build an empirical model that maps the observables and models data to a prediction of the turbulence," he says.

"That works by taking a set of data and training an ensemble of decision trees, each on a random subset of the data and only allowed to use a certain number of predictors. You train up about 200 decision trees, each able to vote on the classification of a new situation and, based on the distribution of those votes, you can relate to a probability of where turbulence is likely to be. That seems to be working pretty well, although we haven't applied it yet to the global turbulence problem—just to predicting thunderstorms over the U.S. and convective turbulence."

Spotting clues

Another useful weather feature is called overshooting tops—cloud towers that have punched through the general cloud top, indicating the greatest area of strong updrafts and, if associated with precipitation, leading to strong downdrafts and so a good chance for severe turbulence. Other factors, such as features associated with the jet stream, also are considered, because turbulence itself is too small to be seen.

"The average area of turbulence is only about 10 to a few hundred meters, and satellites can only see [weather] features down to about 1 km in length or breadth—but we can see areas where turbulence is likely to occur," Murray explained. "So a main satellite function is actually to help us rule out areas least likely to have turbulence.

"Turbulence actually is most damaging when the area is about the same size as the aircraft itself. If you have an area that is very strong and only 100-1,000 ft long, all that energy is concentrated like a punch. And that's where people standing in the aisles hit the top of the cabin when the aircraft drops or rises abruptly."

Part of the current NCAR effort is to study more closely elements associated with thunderstorms over land, such as height, size, and intensity, and how they are likely to be related to turbulence, then apply those measurements to satellite data. Because ground-based radars and other measurements used in the forecasting methodology over land are not available over water, identifying commonalities that can be seen with both is crucial to enhancing oceanic forecasting.

from a variety of sources that is then weighted based on reliability, timeliness, and other factors. Satellite data can be the first indication of possible trouble in areas without radar coverage or regular traffic routes, filling in data gaps through examination of such things as gravity wave patterns in clouds; turbulence often is associated with breaking waves. Another technique called "random forests," first identified in 2001, also can be applied, according to John Williams, NCAR's GATDSSA project lead.

"The basic idea is to take a set of data in which you associate a number of predictors with a predictant—in our case, taking various

Aid from advanced space systems

Advanced satellite technologies now coming online or due in the near future also will substantially improve weather-related data available to turbulence prediction and detection. For example, the MODIS (moderate resolution imaging spectroradiometer) imager now flying on NASA's Terra and Aqua Earth orbiting satellites can see down to 250 m, very close to the scale of turbulence.

Higher resolution sensors coming online include imagers that look at visible light, providing not just pictures but energy measurements at different wavelengths. By looking at the differences in multiple data channels, researchers can tell if the cloud tops are cooling quickly, indicating rapid convection. Other sensors called sounders look at the infrared portion of the spectrum, providing information on relative humidity and temperature at different altitudes. Balloon sounders currently are used for that, along with some on satellites, but future satellite sensors will be much more sophisticated.

"In a few years, we will have even higher resolution imagers on the GOES series; around the midteens, the GOES-R satellite will have an advanced imager, and eventually these experimental sensors will become standard," Murray says. "GOES-R also will have a lightning sensor, and the polar orbiting satellites will have instruments measuring profiles of temperature and water vapor—the starting point for all weather forecasts.

"If you look at the GTG model, it starts out using information from NOAA's rapid update cycle," Murray continues. "The RUC tells the temperature and water vapor levels for the next 6 hours and is the finest resolution instrument we have for that. By looking at the RUC profiles, the GTG can tell what the stability of the atmosphere will be at a particular location."

While NASA satellites are being used in developing the system, Williams adds, they will serve primarily for verification and tuning, rather than data-gathering, in an operational system. "We are using primarily operational environmental satellites, such as NOAA's GOES, and hope to use the European Media-Sat and Japanese 1R satellites. The NASA satellites are, by and large, polar orbiters and make occasional stripe measurements, so we really can't base a product on them," he says.

"But we can use some advanced NASA research satellites to verify the products we develop based on the others. For example, there is a satellite with a down-pointing radar
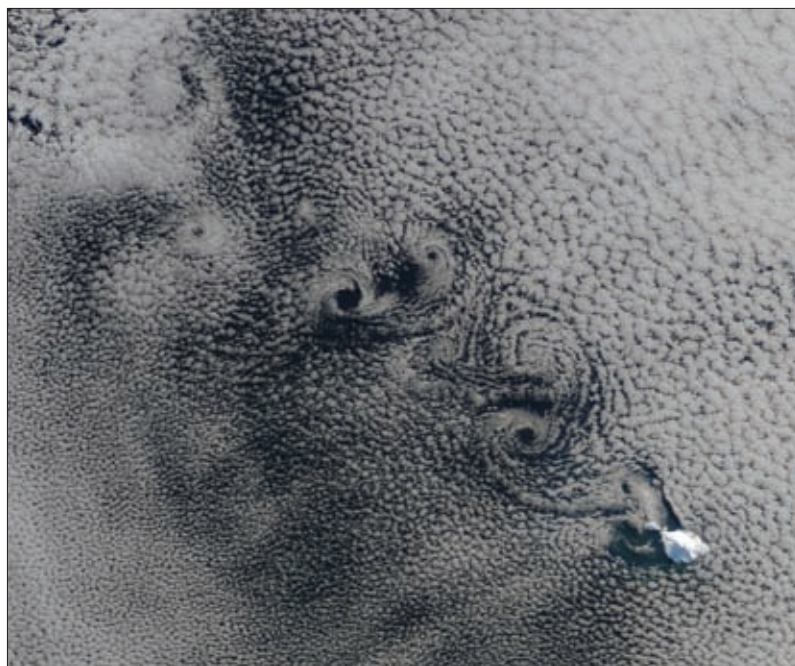
MODIS can see down to 250 m, very close to the scale of turbulence, and so aids in turbulence prediction.

that can really characterize what the storms look like as it flies over that strip; we can use that to verify that the information we have on that storm, based on the environmental satellites, is correct."

The size factor

Because of the actual size of areas of turbulence, the impact varies greatly with the size of the aircraft—as does the best course of action for the pilot to take.

"Turbulence operates at the scale of the aircraft, so if the area of turbulence is smaller than the aircraft, it might be felt as just a little high-frequency chop, where an aircraft the same size as the turbulence would have a much higher level of problem," Murray explains. "The size of the aircraft and its configuration, amount of fuel, whether it has passengers or cargo, all change the loading. What a 747 might not even feel or a 737 might feel as light to moderate turbulence,

"For nonfatal accidents, turbulence is the number-one cause of injury to flight crews and passengers, especially flight attendants, who spend so much time on their feet." – JOHN MURRAY

someone in a smaller aircraft might experience as severe turbulence."

Thus the cost of diverting may be significantly higher than the benefit of any evasive action for a "big heavy" than for a lighter aircraft. In addition, some new aircraft are de-

signed with some measure of turbulence mitigation built in, so even if all other factors are identical, the pilot of a new model might make a different decision from the one made by the pilot of an older aircraft from the same family.

Researchers also are developing or enhancing other ways to measure encountered turbulence and determine the best approach for a variety of aircraft that may be on course to encounter it next.

"In-situ turbulence reporting is a system developed by NCAR to turn the airplane into a turbulence monitor," Williams says. "That uses the eddy dissipation rate [EDR]—measuring the rate at which energy flows from large-scale forcing mechanisms down to smaller scale eddies. The scaling from EDR to a particular aircraft depends on its speed, weight,

The GTG combines and assigns weight information from a variety of sources.

and wing area. We take the reporting aircraft's independent measurement and can scale it back to apply to any particular aircraft type and operating conditions.

"That gives us routine, objective measurements of turbulence, which are key to developing relationships of what can be measured by satellite, from the global forecast system model and the aircraft measured turbulence, using AI [artificial intelligence] techniques to sort through all this data and uncover those relationships, which we then will apply globally."

Communicating the results

Currently, the global forecast model run by the U.S. National Weather Service provides 3D forecasts of wind, temperature, stability, humidity, and other environmental features around the world. The data will be used to derive diagnostics of turbulence and combined to form an estimate of where it is likely to occur.

"So the various satellite systems, the AI methodology of random forests, etc., are put together, using some pretty fast computers to process it all with minimum latency to get information to decision-makers. In a year, we plan to demonstrate cockpit uplinks of customized maps of turbulence ahead of oceanic flights; for that, we send a text message to ARINC that will be downlinked via satellite to the ACARS [aircraft communications addressing and reporting system] printer, which is an enabler for that cockpit uplink," he says.

"We will have a Web link for pilots to review the messages they receive and provide feedback. We also will have a Web-accessible link, using Java, based on a system called the Aviation Digital Data Service, for dispatchers, air traffic controllers, and anyone else interested, but next year probably only visible to selected United Airlines dispatchers. It will be a few years before it would be FAA approved and publicly accessible."

The system is being designed to avoid the need for any additional cockpit hardware, Williams adds, although additional pilot training may be required down the line.
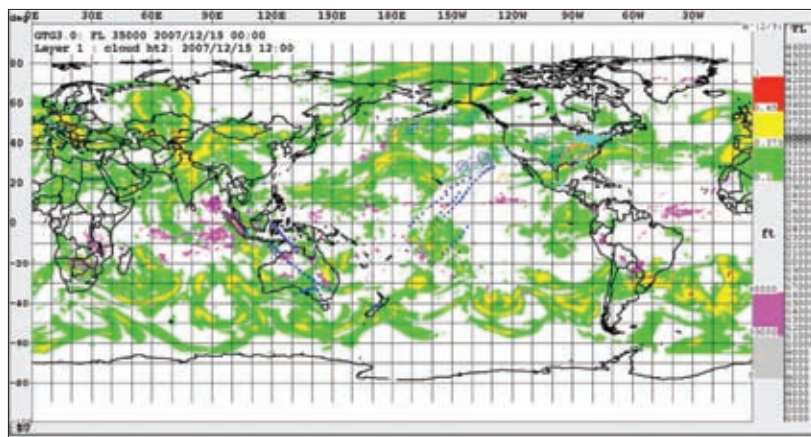
"We're doing our best to focus on the atmospheric science problems of predicting thunderstorms and turbulence, making use of available data feeds and technologies, such as uplinking a text graphics map to ACARS," he notes. "We would prefer a graphical color map, but we're focusing on the aviation weather problem, not the dissemination problem. So it will print out on the same strip printer as other ACARS messages in the cockpit, which is a new use of an existing product.

"We hope, in two years, we can make the system available to the FAA for evaluation as part of the NextGen operational capability in 2013, where it would be run routinely by the FAA Tech Center or National Weather Service. The grids would be made available for airlines or private vendors to use as they see fit. We hope that will mean inclusion in electronic flight bags currently under development to provide pilots with graphical displays of a variety of weather data in the cockpit—and that certainly will require some additional pilot training."

At the same time, any such system will have to avoid creating information overload for the pilot.

Managing the load

"One thing we studied under our last aviation weather program was how much of a pilot load, with respect to weather [information], can be managed effectively. We learned it is best to give a pilot only what he needs. He

> **"Our goal is to give pilots a regularly updated picture of the likely storms ahead as they fly over the ocean, so they can take action to minimize turbulence and keep their aircraft out of danger."** – **CATHY KESSINGER**
> **NCAR project scientist**

has too many other things to manage to be looking at weather maps in the cockpit, so any information you provide has to be very specific and tailored specifically to his need," Murray says.

"This is an evolutionary question. There is an ATC [air traffic controller] there now, because he has information the pilot doesn't. If the pilot has better information, it might be better to let him make decisions now made by others, especially if he can make a better decision. But until the information is better, the workload is divided to take advantage of the fact the ATC knows things the pilot doesn't.

"The whole purpose of NextGen is to use automated tools to help manage this vast amount of information without overwhelming the pilot," says Murray. "As the FAA and airlines examine the quality of information they get through NextGen, the question becomes 'When, and to what degree, do we give pilots more autonomy?' In a typical en route scenario, with aircraft spaced out every 5 mi. and 2,000 ft, if the pilot gets information that would avoid or reduce turbulence, there's no reason not to independently change altitude or heading. Right now, however, there are too many factors to make that determination."

The information now being developed under the NCAR program, together with other NASA, NOAA, FAA, and academic research, has been identified as critical for NextGen, Murray says, and especially for its 4D Network-Enabled Weather System. The long-term goal of that network-centric, Internet-based approach is for every system aboard an airplane to have an IP address, making the relationship between all aircraft, satellite, and ground systems similar to that of all the networked computers in an office.

"NextGen will use a standard database, and all ATM [air traffic management] will be based on a very strict data set, called the single authoritative source. And I tend to think weather information associated with that will be much higher quality and will have some probabilistic components, such as saying, 'Here's where we expect convection to be in 1 hr with 85% confidence and in 2 hr with 35% confidence,' and so on," Murray says.

"That information and those probabilities will be constantly updated and improved, because weather is nonlinear and chaotic, which is why weather forecasts are less reliable the farther out you try to go. If you get one observation just a little wrong, it can throw the whole forecast off."

Parallel efforts

NextGen and its weather component involve efforts by a wide range of government agencies, industry and industry organizations, and academia, including international collaboration. Those range from the FAA, NOAA, NASA, and NCAR to the American Meteorological Society's Aviation Range and Aerospace Meteorology Group and AIAA's Atmospheric and Space Environments Technical Committee to NASA's Aeronautical and Space Operations Subcommittee. Those and others work closely through an interagency/industry partnership program to coordinate their efforts.

That also applies to ongoing efforts in Europe and Asia to develop similar systems, including a global standard to deal with weather information. Thus while each effort is primarily designed to develop a new airspace system for a nation or region, each also must deal with aviation as a global enterprise. The same aircraft may fly through multiple jurisdictions on a single flight, but will need a coordinated set of rules and information provision to do so safely and efficiently.

"I think we can improve safety, efficiency, and passenger comfort by providing an automated system, with minimal latency, to help pilots, dispatchers, and air traffic controllers make better decisions on how to route the aircraft and when to divert or prepare for encounters with pockets of turbulence," Williams concludes.

"Our system will indicate something about storm height and intensity, which includes the hazard of turbulence, but also water temperature and the possibility of hail and lightning. So even though turbulence is the primary goal of our system, if you know where the storms are and their intensity, these other hazards also might be avoided." Ⱥ